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Recent Advances in Base Isolation Technology

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ABSTRACT

Base isolation is a technology that is widely accepted by the profession as an effective means to protect structures and non-structural components against earthquake damage. This is demonstrated by the large number of buildings and bridges that have been built or retrofitted using this technology. It is contended, however, that, at present, the existing isolation systems have limitations and that these limitations have prevented a widespread use of the technology in ordinary structures and in developing and emerging countries. It is the purpose of this paper to make a brief review of the predominant isolation systems, pinpoint their major disadvantages, and describe some of the solutions that have been proposed to overcome these disadvantages. The systems considered are (a) laminated elastomeric bearings, (b) friction pendulum bearings, and (c) sliding bearings. Special attention is given to the description of two recently proposed sliding systems that incorporate unusual features: (a) hydrostatic bearings, and (b) hydromagnetic bearings. The review reveals that many researchers are still active in the base isolation field and that many interesting improvements have been proposed over the last few years.

Keywords:
Seismic isolation;
Isolation bearings;
Earthquake protective systems;
New technologies

1. Introduction

It can be said that, currently, base isolation technology is an established field, widely accepted by the profession as an effective means to reduce structural and nonstructural damage during earthquakes. Evidence of this is the large number of buildings and bridges that have been constructed using this technology. Some of the latest statistics in this respect show that the number of applications is over 5,000 in Japan, 400 in China, 550 in the Russian Federation, 90 in Italy, 80 in the United States, and 32 in Armenia. Of the types of isolation systems used in actual implementations, three of them seem to be the predominant ones. These are: (a) laminated elastomeric bearings, (b) friction pendulum bearings, and (c) sliding bearings. It is interesting to know, however, that despite their popularity, these systems still have some limitations and that these limitations, for the most part, have prevented their widespread use. That is, they have prevented their use in ordinary structures and in developing and emerging countries.

In general, it seems that the major limitations that have impeded a wide use of the technology are [1]:

- Knowledge gaps (many aspects of device and system response still unknown);
- Procedural obstacles (design methods difficult and code provisions burdensome);
- Economic barriers (technology still too expensive for ordinary structures).

To overcome these gaps, obstacles, and barriers, improvements to the predominant base isolation systems have been proposed over the last few years. It is the purpose of this paper to present a brief review of the main characteristics of such predominant systems, pinpoint their limitations, and describe some of the aforementioned improvements. The objective is not to present a comprehensive state-of-the art report. The objective is, rather, to highlight the advances made in this field and show that these advances hold a promise toward the achievable goal of a simple, reliable and inexpensive isolation system that can facilitate a wider implementation of base isolation. Emphasis is placed on the description of two particular sliding systems: (a) hydrostatic bearings, and (b) hydromagnetic bearings. These two systems depart significantly from conventional sliding bearings and require a more detailed description.

2. Laminated Elastomeric Bearings

2.1. General Characteristics and Main Disadvantages

As is well known, a laminated elastomeric bearing is formed with thin sheets of steel and rubber (or any other elastomer, such as neoprene) built up in layers and bond together by vulcanization. In addition, thick steel plates are bonded to the top and bottom surfaces of the bearing to facilitate the connection of the bearing to the foundation and the superstructure. A rubber cover is used, too, to wrap the bearing and protect the steel plates from corrosion. Because of the low shear modulus of rubber, laminated elastomeric bearings possess a large horizontal deformability and may thus elongate the natural period of the structure they support. If flexible enough, they may therefore be used to change the fundamental natural period of a structure to a value that is sufficiently away from the dominant periods of the expected earthquakes. This way, resonant motions are avoided and the structure is protected against severe earthquake damage.

Although effective to protect structures against earthquake damage, laminated elastomeric bearings present the following disadvantages:

1. They may amplify long-period ground motions in a way that may affect long-period nonstructural components.
2. They may be subjected to large lateral deflections, requiring thus a large isolation gap to accommodate these lateral deflections.
3. They are always in danger of an insufficient isolation gap and thus of unpredictable impact effects if the bearings pound against restraining elements.
4. They are susceptible to buckling if subjected to large deformations and heavy vertical loads.
5. Because their manufacturing process is quite elaborate, and they are usually heavy, their cost and the cost of their implementation are high.

To overcome these disadvantages, laminated elastomeric bearings are usually implemented in conjunction with supplemental dampers or energy dissipation mechanisms that reduce their deflections to practical levels. However, the cost of these supplemental dampers or energy dissipation mechanisms and their implementation add significantly to the already high manufacturing cost of the bearings themselves. In addition, the bearings' implementation usually requires the construction of rigid diaphragms (floor systems) above and below the bearings to uniformly distribute the lateral loads to each of them. The construction of an additional floor system also adds significantly to the cost of base isolating a structure with laminated elastomeric bearings.

2.2. Proposed Improvements

It may be seen, thus, that the main disadvantage of elastomeric bearings is their high relative cost. For this reason, several proposals have been made in the last few years to reduce this cost. Some recent proposals are:

1. Place isolators on top of the ground-floor columns to avoid the construction of a double floor system [1], see Figure (1).
2. Use several small bearings as opposed to a single heavy one to reduce construction costs [2], see Figure (2).
3. Use laminated rubber bearings constructed with

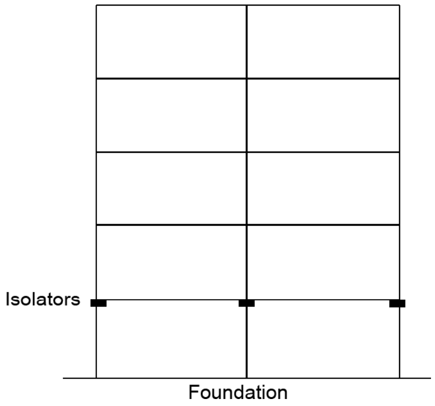

Figure 1. Bearings on top of ground-floor columns in base-isolated building.

scrap tires to reduce manufacturing costs [3], see Figure (3).

4. Use scrap rubber tires filled with crushed rock as bearings [4], see Figure (4).

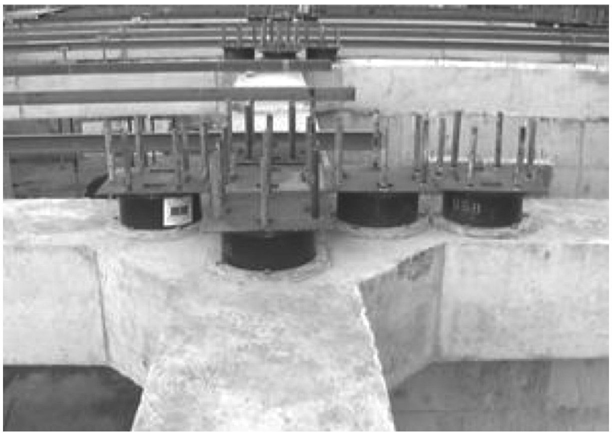

Figure 2. Example of installation of multiple rubber bearings under one column [2].

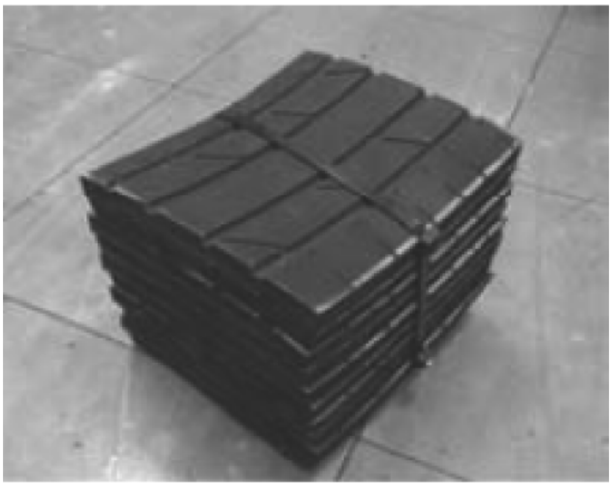

Figure 3. Rubber bearing manufactured with scrap rubber tires [3].

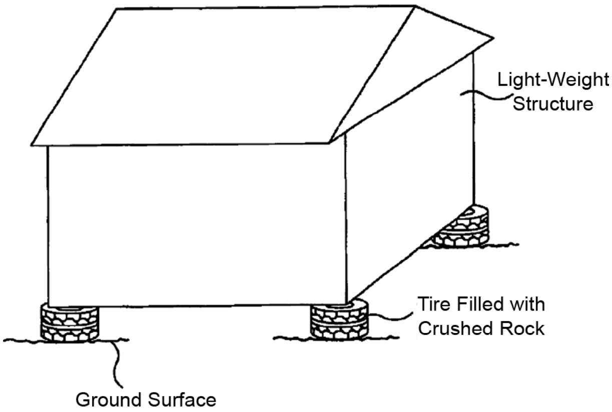

Figure 4. Light-weight structure isolated with tires filled with crushed rock [4].

3. Friction Pendulum Bearings

3.1. General Characteristics and Main Disadvantages

The friction pendulum bearing is a sliding isolator consisting of an articulated slider that moves on a concave spherical stainless-steel surface. It also includes an enclosing cylinder that provides a lateral displacement restrain and protects the interior components from environmental contamination. The articulated slider is coated with a low-friction and high-pressure capacity composite material (typically *PTFE*-based materials). Because of the friction between the sliding surfaces, a structure supported on friction pendulum bearings responds to low-level forces like a conventional fixed-base structure. Once the friction forces are exceeded, however, the structure responds as a free pendulum with the dynamic response controlled by the natural period of this pendulum and the damping generated by the frictional forces. As in the laminated elastomeric bearing case, seismic isolation is achieved by lengthening the natural period of the supported structure. However, the friction pendulum bearing also has a re-centering capability. This re-centering capability results from the fact that as the slider moves along the spherical surface, the supported structure rises and develops by gravity, a restoring force that helps bring the structure back to its original position.

The friction pendulum bearing offers the advantage of combining the basic elements of an isolation system in a compact unit and has at the same time an inherent re-centering capability. Despite these advantages, friction pendulum bearings also have the following limitations:

1. They possess a long natural period, and consequently, the isolated structure may be affected by long-period ground motions.
2. The generated restoring force and the damping force are transmitted to the structure.
3. The restoring force varies linearly with the sliding displacement; therefore, the bearings may not be effective for severe ground motions as the force transmitted to structure increases with the sliding displacement.
4. If the coefficient of friction is low, the sliding displacements and transmitted forces may be large even for moderate ground motions.

5. If the coefficient of friction is high, the isolation system may not activate and thus may not be effective under minor events. Also, re-centering of the structure becomes an issue.
6. The bearings are effective for only one excitation level; that is, the bearings may be designed to attain satisfactory performance under only one excitation level.

3.2. Proposed Improvements

It seems, thus, that the major disadvantage of friction pendulum bearings is their inability to perform satisfactorily under low-level events if designed to perform effectively under high-level events, and vice versa. In a time where performance-based design is being widely adopted by building codes, this disadvantage becomes a serious deficiency. In response to this deficiency, several modifications have been proposed. Some of these modifications are described below.

3.2.1. Variable Frequency Pendulum Bearings

The variable frequency pendulum bearing, proposed by Pranesh and Sinha in 2000 [5], is similar in construction and operation to the friction pendulum bearing. The difference is that a non-spherical surface is used instead of the spherical one used in the friction pendulum bearing. The non-spherical surface is given by series of progressively larger ellipses, leading to a flatter shape that approaches that of a flat bearing. For comparison purposes, Figure (5) shows the shapes of a conventional friction pendulum bearing and the variable frequency pendulum bearing when both are designed for an initial natural period of 2.0*s*. The advantages of using a non-spherical sliding surface are as follows:

- The bearing's natural period of isolation lengthens with sliding displacement;
- The bearing is insensitive to the long-period com ponents of high-level excitations;
- The restoring force decreases with sliding displacement and thus the force transmitted to the isolated structure is limited to an upper bound;
- Its performance is similar to that of a friction pendulum bearing for low-level excitations and similar to that of a flat sliding bearing for high-level excitations;
- It allows the use of surfaces with low friction as the magnitude of the force transmitted to the structure (restoring force) during high-level excitations is relatively small;
- With it, the structural accelerations transmitted to the structure and the sliding displacements are both smaller in comparison with those observed in a friction pendulum bearing; hence, it offers an overall better performance.

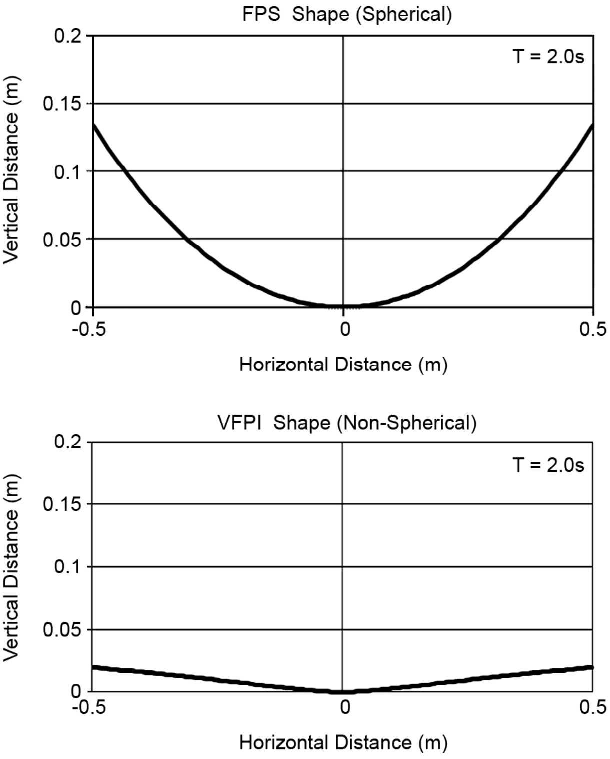

Figure 5. Sliding surfaces in friction pendulum and variable frequency pendulum bearings [5].

3.2.2. Triple Friction Pendulum Bearings

The triple friction pendulum bearing is also similar in concept to the conventional friction pendulum bearing, but as its name indicates, it is composed of three sliders as opposed to the single one used in the conventional friction pendulum bearing. It also has four sliding surfaces instead of just one. The properties of the components are selected to activate the inner slider first and then the other two sliders sequentially under increasingly stronger ground motions. Introduced by Fenz and Constantinou in 2008 [6], the central idea is to provide a combination of different surfaces with different coefficients of friction and radii of curvature upon which the sliding can take place. This, in turn, provides the flexibility for designs that can be separately optimized for different levels of ground shaking. That is, a triple friction pendulum bearing can be equally effective under low- and high-level excitations. Its main advantages may be summarized as follows, see Figure (6):

- Triple friction pendulum bearings are capable of adjusting their stiffness and damping properties according to the excitation level;
- With triple friction pendulum bearings, the natural period of the isolated structure is short and its effective damping is small under the low-intensity excitations, resulting in low in-structure accelerations under these excitations;
- Similarly, the natural period of the isolated structure and its effective damping increase under high-intensity excitations, resulting in lower base shears and lower bearing displacements under such excitations;
- As a result, triple friction pendulum bearings reduce the size and cost of the required bearings and the size of the isolation gap needed to accommodate the bearings' displacements.

4. Sliding Bearings

4.1. General Characteristics and Main Disadvantages

In its basic form, a sliding bearing is composed of two stainless steel plates and a low-friction Teflon disk in between. It is placed between a structure and its foundation, with one of the steel plates connected to the superstructure and the other steel plate and the Teflon disk connected to the foundation. It provides a mechanism to let the isolated structure slide under lateral loads that exceed a certain threshold level. Sliding bearings allow thus the transmission of shear forces from the ground to the superstructure up to a particular level, beyond which sliding occurs and a further transmission is prevented. The magnitude of the forces transmitted to the superstructure during an earthquake is more or less independent of the severity of the earthquake.

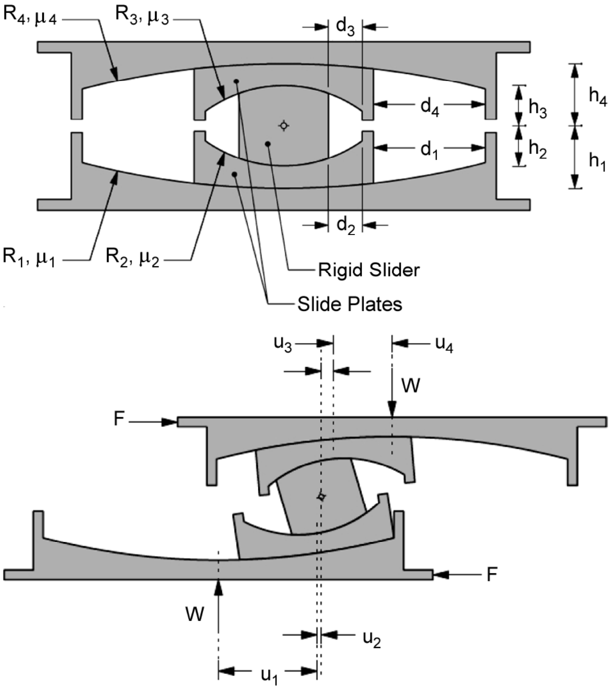

Figure 6. Central and displaced configurations of triple friction pendulum bearing [6].

Sliding bearings are very efficient in mitigating the effects of earthquakes. Furthermore, they are relatively inexpensive and compact in size. However, they have the following limitations:

- If used alone, there is no restoring force; in consequence, the bearing and residual displacements may be impractically large;
- Sliding bearings are thus commonly used in combination with a re-centering mechanism that adds to the cost and complexity of the bearings (external elastomeric springs, laminated bearings, or internal rubber cores have been employed);
- Friction prevents the sliding of the bearings under low-intensity excitations; so, if the coefficient of friction is high, the forces transmitted to the structure may be significantly large;
- The sudden sliding that takes place after the friction forces are overcome may induce high-frequency structural vibrations that may be detrimental to nonstructural components;
- The magnitude of the friction forces and the performance of the isolated structure may be affected by the vertical ground accelerations;
- The frictional properties of sliding bearings are affected by the composition and conditions of the sliding interface, bearing pressure, sliding velocity, contamination, and temperature;
- Pure Teflon is a soft plastic material that is generally mixed with additives to increase its capacity to endure large axial forces; however, this also increases its friction coefficient.

4.2. Proposed Improvements

4.2.1. Supplemental Pressurized Spring Dampers

The idea behind this proposal is simply to combine conventional steel-Teflon sliders with high-performance pressurized spring dampers [7], see Figure (7). These dampers work as ordinary viscous

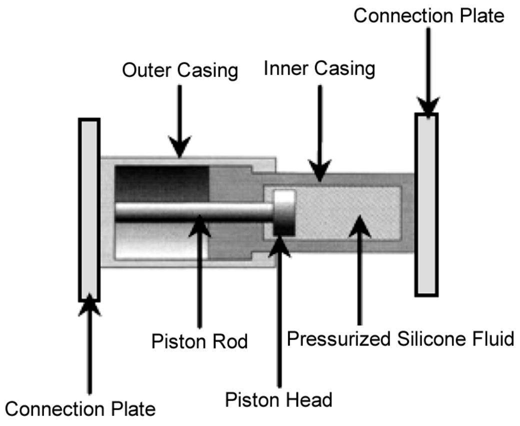

Figure 7. Pressurized viscous spring damper [7].

dampers but are pressurized to provide for a restoring force. They offer thus the advantage of providing a restoring force and a damping mechanism to sliding bearings with a simple, compact, and inexpensive unit. They provide an economical alternative to overcome the disadvantages of sliding bearings.

4.2.2. Hydrostatic Bearings

Hydrostatic bearings are a low-friction alternative to steel-Teflon sliding bearings that use no Teflon and therefore, are unaffected by the low bearing capacity of this material. As shown in Figure (8), a hydrostatic bearing is composed of a steel cylinder, a mounting steel plate, an X-shaped elastomeric O-ring, and a low-compressibility viscous fluid. The steel cylinder is machined to form a fluid chamber, a groove to lodge the elastomeric O-ring, and a small orifice for the pouring and extraction of the fluid from the chamber and to connect a pressure gage. The groove depth is such as to let the elastomeric O-ring protrude beyond the lower surface of the steel cylinder. The O-ring hermetically contains the fluid in the fluid chamber and is free to slide together with the steel cylinder, on top of a highly polished steel plate attached to the foundation. The mounting plate is welded to the upper part of the steel cylinder and connected to the structural element supported by the bearing.

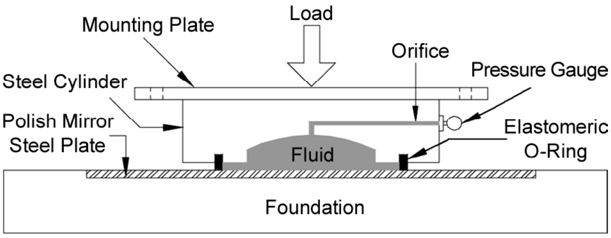

Figure 8. Schematic representation of hydrostatic bearing.

The advantages of hydrostatic bearings are many:

- They are simple and economical to build;
- The only sources of friction are the shear resistance of the viscous fluid and the friction between the O-ring and the supporting plate;
- As such, the sliding friction and the shear force they transmit to the superstructure are insignificantly small;
- Since they are activated under a very small force, they are effective under low- and high-level excitations;
- By the same token, the impact effects caused by the sudden breaking of the friction forces between the bearing and its supporting plate are insignificantly small;
- Since they have no natural period, they are insensitive to the frequency characteristics of ground motions;
- With them, the vertical load and the vertical reaction at the isolation interface are always aligned (no load eccentricity); therefore, they are not prone to buckling.

To prove that hydrostatic bearings indeed work well, Carnalla [8] conducted experiments in a shaking table with a three-story steel structural model, see Figure (9). The model has a height of $2.3m$ and plan dimensions of $1.52m$ by $1.52m$. It was first tested under fixed base conditions and then in isolated conditions using hydrostatic bearings. The bearings used are also shown in Figure (9) without and with the chamber fluid (*SAE* 100-140 oil) and the elastomeric O-ring. In each case, the model was subjected alternatively to three different base motions (earthquake acceleration records). A comparison was made of the structural response in each case and in all instances a significant reduction in structural response was obtained when the model was isolated with the hydrostatic bearings. In each case, too, the bearings performed as expected, with no oil leaks and keeping their integrity at all times.

4.2.3. Hydromagnetic Bearings

As described in the previous section, hydrostatic bearings are exceptionally effective in reducing the magnitude of the forces transmitted to a structure during an earthquake. However, as in the case of a basic sliding bearing, they lack a re-centering mecha-

Figure 9. Machined cylinder, O-ring, hydrostatic bearing, and isolated structural specimen [8].

nism that can bring the structure back to its central position after an earthquake. They also lack a damping mechanism to reduce the sliding displacements to a practical level. To overcome these disadvantages, the author has come up with an idea to incorporate re-centering and damping mechanisms in hydrostatic bearings in a simple way. As described below, the idea consists of using permanent magnets. For this reason, the modified hydrostatic bearings are referred to as "hydromagnetic bearings".

As shown in Figure (10), a hydromagnetic bearing is composed of an annular permanent magnet, upper and lower pieces of mild steel, two sealing gaskets, an elastomeric O-ring, and a low-compressibility viscous fluid. As in the case of hydrostatic bearings, the bearing slides freely on top of a supporting plate. The upper mild-steel piece is cylindrical in shape and is attached together with one of the sealing gaskets to the top of the annular permanent magnet. It is also bolted to a steel plate anchored to the inferior face of the structural element it supports. The lower mild-steel piece is annular in shape and is attached together with the other sealing gasket to the bottom of the annular permanent magnet. The two mild-steel pieces are attached to the annular permanent magnet by means of the attraction that exists between a magnet and a steel piece. A groove is formed into the lower mild-steel piece, fitting the elastomeric O-ring into it. The groove depth is such as to let the elastomeric O-ring protrude beyond the surface of the mild-steel piece. The elastomeric O-ring is of the X-shaped type to provide twice the sealing surface in comparison to a standard O-ring and require less pressure to provide an effective seal. The supporting plate is made of aluminum because aluminum is a good conductor of electricity and is also used widely as a structural material. In addition, it is polished to a mirror finish to minimize the possibility of fluid leaks and reduce the friction between the plate and the elastomeric O-ring.

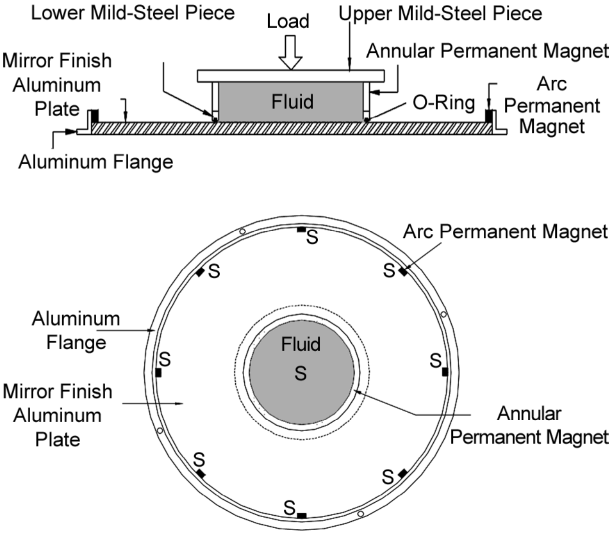

Figure 10. Side and plan views of hydromagnetic bearing, supporting plate, and peripheral accessories.

Together, the annular permanent magnet, the mild-steel pieces, and the elastomeric O-ring form a hermetic fluid chamber. The low-compressibility viscous fluid is contained in this fluid chamber. As in the case of the hydrostatic bearing, a small orifice (not shown) is made into the upper mild-steel piece to be able to pour or extract fluid from the fluid chamber. Also, a pressure gage (not shown) is connected to this orifice to monitor the pressure in the fluid chamber. The low-compressibility viscous fluid may be any oil as long as it is compatible with the elastomer with which the O-ring is made.

The sliding of the bearing is restrained by a series of permanent magnets attached to an aluminum flange placed at the periphery of the supporting plate. This aluminum flange is welded to the edge of the aluminum plate and bolted down to the foundation.

The peripheral permanent magnets are arranged symmetrically and equally spaced in the interior of the aluminum flange. Their orientation is such as to produce repulsive forces on the annular permanent magnet, e.g., the south poles of the peripheral magnets should face the south pole of the central magnet (the "*S*" symbols in Figure (10) refer to the magnets' south poles). As magnets cannot be drilled or welded, they are fastened to the aluminum flange using mechanical means (e.g., clamps). The preferred shape for the peripheral permanent magnets is the shape of a circular segment (arc magnets). However, any other shape may be used. Because of their high strength, the annular and the peripheral permanent magnets are of the neodymium-iron-boron type.

Hydromagnetic bearings operate in much the same way as the hydrostatic bearings described in the previous section. The difference is that in the case of the hydromagnetic bearings there are two other forces that, to some extent, restrict the motion of the bearings. The first of such other forces is a damping force generated by the motion of the annular permanent magnet over its supporting aluminum plate. This force appears and slows down (damps) the annular permanent magnet's motion because:

- The annular permanent magnet generates a magnetic field in its surrounding space;
- When the annular permanent magnet is in motion, the intensity of the generated magnetic field at any given point in space changes with time;
- According to Faraday's law, a changing magnetic field induces in a nearby conducting material electric currents known as eddy currents;
- Aluminum is a conducting material;
- According to Biot and Savart's law, these eddy currents induce, in turn, a secondary magnetic field in the surrounding space of the conducting material;
- According to Lenz's law, this secondary magnetic field generates a force on the annular permanent magnet that opposes its motion.

The magnitude of the damping force just described depends on the size and grade of the annular permanent magnet and the thickness of the aluminum plate. The amount of damping introduced into the isolation system may be thus controlled by changing some or all of these parameters. The damping force generated by the motion of the central permanent magnet will undoubtedly reduce the peak sliding displacement of the bearing during an earthquake in comparison with the one that would be observed in a similar bearing but without a damping mechanism. It should be noted, however, that such a reduction is realized at the cost of increasing the shear forces transmitted to the superstructure. Thus, the amount of damping introduced into the isolation system should be such that, on one hand, reduces the bearing's peak sliding displacement to an acceptable level and, on the other hand, does not increase excessively the shear forces transmitted to the superstructure.

The second of the forces that restrict the motion of a hydromagnetic bearing is the resultant of the repulsive forces on the annular permanent magnet exerted by the peripheral permanent magnets, see Figure (11). These repulsive forces arise because of the well-known fact that the like poles of two magnets repel each other, and because, as installed, the like poles of the peripheral permanent magnets and the annular permanent magnet always face each other. The magnitude of the repulsive forces and, hence, the magnitude of the resultant force acting on the annular permanent magnet depend on the strength of the peripheral and annular permanent magnets, their size, the distance between them, and the number of the peripheral permanent magnets installed.

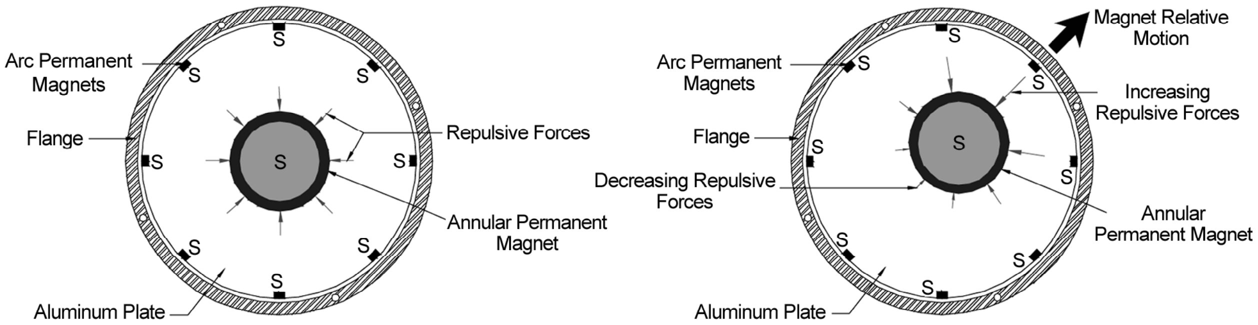

Figure 11. Repulsive forces in central and displaced positions of annular permanent magnet.

For a given set of magnets, the magnitude and direction of the resultant force acting on the annular permanent magnet depend thus on its position relative to its initial central position, see Figure (11). Because of the symmetrical arrangement of the peripheral permanent magnets, the resultant of the repulsive forces on the annular permanent magnet is equal to zero when it is in its central position. However, if the annular permanent magnet is displaced from its central position, some of the repulsive forces will increase, and some others will decrease. In this case, therefore, the resultant of the repulsive forces will be a force that opposes the motion of the annular permanent magnet and will bring it back to its central position in the absence of any other external forces, see Figure (11).

As the magnitude of the repulsive forces between two magnetic poles decays rapidly with distance, the force opposing the motion of the annular permanent magnet (restoring force) will be a small one if the annular magnet is near its center, but it will be a strong one if it is near the edge of the aluminum plate. This offers the double advantage of allowing the bearing to displace more or less freely under earthquakes that are equal or smaller than the design earthquake, but restricting its motion in the event of unexpectedly large earthquake. It should be noted, however, that, as in the case of the damping force, a restoring force is transmitted to the superstructure. The peripheral permanent magnets should be thus used to generate the minimum restoring force that is required to bring the bearing back to its original position after an earthquake. In this regard, it is worthwhile to note that in the case of a hydromagnetic bearing, this minimum restoring force is not too large because: (a) the force that needs to be overcome for the re-centering of the bearing is the friction force between the O-ring and the aluminum plate, and (b) this friction force is, as stated earlier, a small one.

It may be seen that a hydromagnetic bearing operates on the basis of a hydrostatic technique that minimizes the sliding friction between the bearing and its supporting plate, a magnetically induced damping force that reduces the bearing's peak sliding displacement, and peripheral permanent magnets that provide a re-centering force and protection against excessively large displacements. Furthermore, it does so (a) with a device that is simple and inexpensive to construct, (b) with components that are commercially available and require minimum maintenance, (c) without the need for a power source, (d) without the need for bulky dampers that take up space, (e) with no impact effects, and (f) without amplifying the long-period components of ground motions. Hydromagnetic bearings, therefore, offer the advantages of conventional sliding bearings but overcome in a simple manner their major drawbacks.

5. Concluding Remarks

A brief review has been presented of the advances made in the field of base isolation technology over the last few years. For the most part, these advances have taken place in an effort to overcome the deficiencies observed in the isolation systems that are predominantly in use today. The review has, thus, pointed out what these deficiencies are, and how they have prevented a widespread use of what is considered a well-established technology. It has also revealed that many researchers are still active in this field and that many interesting improvements have been proposed and, without doubt, will be proposed in the near future. It is likely, therefore, that soon, somebody will come up with a simple, reliable and inexpensive system that can facilitate the implementation of base isolation technology in ordinary structures and all over the world. It can be said with confidence that, despite its current limitations, base isolation is and will always be a useful tool in the toolbox of structural engineers.

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